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Delamination Characterization and Comparative Assessment of Delamination Control Techniques in Abrasive Water Jet Drilling of CFRP

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Abstract
Composite laminates are used in many applications in industries like aerospace and aircraft due to their extremely high strength to weight ratio and corrosion resistance properties. The composite laminates are difficult to machine materials, which results into low drilling efficiency and drilling-induced delamination, thus it is important to develop an innovative advanced drilling process to overcome the difficulties related in the machining of composite materials. This work is focused on comprehensive experimental characterization to understand the effect of cutting parameters on the delamination extent during abrasive water jet drilling of carbon fiber reinforced polymer. Processing parameters, such as standoff distance and water pressure plays dominant role in delamination than abrasive flow rate. It also describes the development of different techniques for controlling the delamination in abrasive water jet drilling process, such as backup plate, pre-drilled hole and water immersion (under water). The analysis shows that abrasive water jet drilling with backup plate yields lower delamination, hole size variation and hole surface roughness.

Keywords: Abrasive water jet drilling, Carbon fiber composite, Delamination extent, Delamination control Techniques

1 Introduction

Abrasive water jet machining (AWJM) is a non-conventional machining process that is used in automobile, aircraft, chemical processing equipment, spacecraft, marine and sporting goods industries related applications. It is a cold cutting process as compared to the other machining processes. Koenig et al. (1985) explained that this technology is more popular due to its properties, such as absence of heat-affected zone and no residual stresses on the work piece. There has been a growing interest in

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using composite materials in place of conventional materials due to their unique properties, such as extremely high strength to weight ratio and corrosion resistance. As a result, these materials are increasingly being used in aerospace and aeronautical structural applications. These days, the abrasive water jet machining process is also being used in the drilling and cutting of composite materials. Seo et al. (2003) observed that drilling of carbon fiber composite materials with abrasive water jet machining process (AWJ) induces damage, such as delamination, fiber push out, fiber pullout. Consequently, a poor quality hole is obtained either at entry or exit of the drilled composite material. Drilling induced delamination damage is a big challenge in the composites because of the high velocity impact due to the water jet on the composite surface. This defect compromises the mechanical properties of machined composites, such as a substantial reduction in the fatigue strength. Scott et al. (2001) found that the water ingress can occur in the interlaminar space due to high pressure which causes damage to the composite material. Shanmugam et al. (2008) conducted experimental work to minimize the delamination during drilling. Reduction of the jet diameter or decreasing the water pressure can reduce the delamination. In abrasive water jet machining (AWJM) process, water jet washes the eroded material from the surface of the workpiece; therefore, there is no chance of environmental contamination due to fibrous materials. Shanmugam et al. (2008) studied delamination as a function of delay time of abrasive flow rate and predicted the crack length with the help of an analytical model. They observed that with an increase in the water pressure, the surface roughness increased because the water jet possesses high kinetic energy for cutting the composite material. Hashish (1993) found that during hole piercing at high water pressure the delamination occurs along with laminate cracking, breaking and fracture. Note that limited work has been reported on process characterization and delamination control techniques in AWJ drilling of CFRP composites. Hence, the objective of the present work is to experimentally characterize the effect of process parameters on delamination extent. In addition, this paper presents a comprehensive study of different delamination control techniques, such as use of backup plates, pre-drilled holes and water immersion(under water). A comparative assessment of all the different delamination control techniques has also been carried out.

2 Experimental set-up and machining conditions

The basic theme of experimentation is shown in Figure 1. It includes design and development of an experimental set-up. The experiential characterization of abrasive water jet drilling process includes the delamination imaging and hole size measurement analysis.

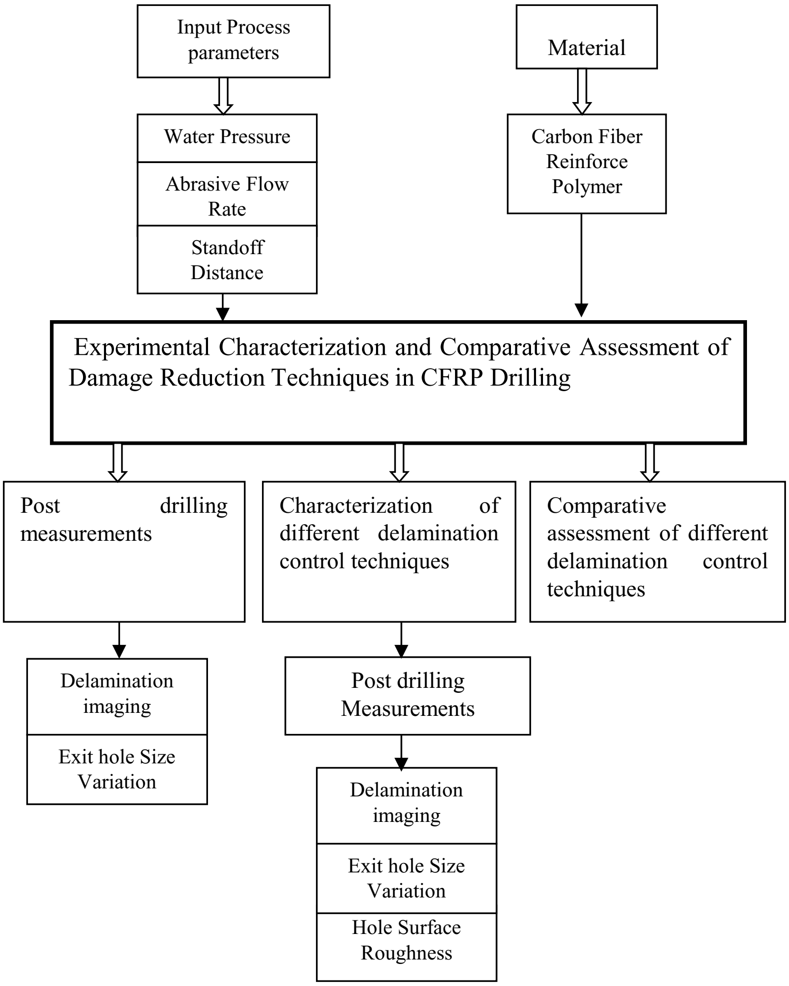
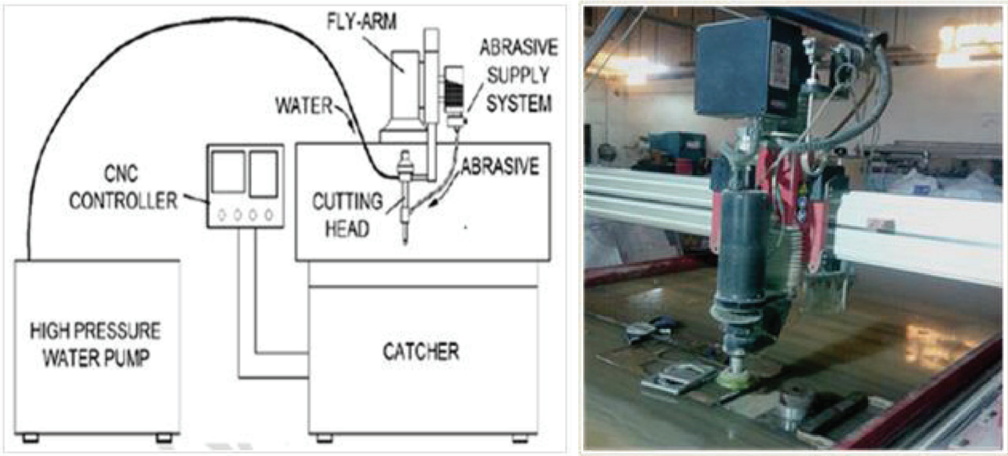


Figure 1: Theme of experimentation.

2.1 Machining set-up

A schematic and experimental set-up for AWJ drilling was shown in Figures 2 (a) and (b). A MAXIEM 1530 three-axis abrasive water jet machine (AWJ) with cutting and taper compensation, rapid water level control and collision sensing terrain facility was used for the experimentation. AWJ machine consisted of a high pressure intensifier pump, abrasive water jet nozzle, catcher tank, abrasive hopper, articulated cutting head and NC controlled by the CNC control system. The intensifier was capable of supplying water up to a maximum pressure of 55,000 psi (380 MPa) and fed to the module called cutting head through the high pressure tube. The high pressure water was then passed through a small orifice (of 0.2 - 0.3 mm diameter), to form a very high velocity jet, which is fed into the mixing chamber to be mixed with abrasives supplied though abrasive supplying system. The abrasive garnet selected had a mesh size of #80. This high pressure WJ comes out of the outlet nozzle of relatively large diameter (0.7 - 0.8 mm). The debris of workpiece material during the experiment was collected into a catcher tank. The position and motion of the cutting head was controlled by computer numerical control (CNC) system.



(a) (b)

Figure 2: (a) Schematic of experimental set-up, (b) Experimental set-up for AWJ drilling tests.

2.2 Design of experiments

The workpiece material used in this study was carbon fiber reinforced polymer (CFRP) consisting of thin layers of carbon fiber (0.007–0.01 mm) prepared from woven WFC200 fabric carbon fiber prepregs. The stacking sequence of all the laminates is $[0/90]_{16.}$ The size of CFRP plate used for experimental work was 150x20x6 mm as shown in Figure 3. The mechanical property of CFRP materials is given in Table 1.

Figure 3: Image of CFRP plate used in experiment.

Table 1: Mechanical properties of CFRP composite

Properties	Symbol	Units	Std. Carbon fiber Fabric
Young's Modulus 0°/90°	E1/E2	GPa	70
In-plane shear Modulus	G12	GPa	5
Thermal Expansion Co-efficient 0°/90°	Alpha 1/2	Strain/K	2.1
Density		g/cc	1.6

A full factorial (3^3) design of experiments was used to investigate the effects of water pressure, abrasive flow rate, standoff distance and cutting parameters on the delamination extent and exit hole diameter. The three factors and their levels are given in Table 2.

Table 2: Factors and their levels

Level	Water Pressure (bar)	Abrasive flow rate (gm/sec)	Standoff distance (mm)
1	1000	5.4	1
2	2000	8.88	2
3	2500	9.7	3

2.3 Experimental procedure

A total of 27 experimental runs with one replication were carried out on CFRP workpiece for the different process conditions. To identify the factors and the levels for the DOE, a number of preliminary drilling experiments (~30) were performed. After the drilling experiment, each hole was subjected to delamination analysis and hole size measurement via Alicona® focus variation microscopy. For exit hole delamination extent and hole size measurement, CFRP plate was mounted horizontally on microscope bed. The scan area was defined by selecting the corner points of a drilled hole and delamination were measured around the hole. The diameter of the best fit circle on the image of the exit hole is used to determine the exit hole size.

3 Results and discussion for delamination extent

During AWJ drilling of CFRP, there are various parameters which affect the quality of a drilled hole. To understand the behavior of exit hole delamination and hole size variation, numerous process measurements were taken. The analysis of full factorial design was made with the help of a software package MINITAB 16.

3.1 Morphology for drilled hole

Exit hole morphologies obtained at different water pressures, abrasive flow rates and standoff distances used in the drilling of CFRP are shown in Figure 5. Delamination is an inter-ply failure phenomenon which can be induced by the drilling of composites. In the present work, the delamination extent (D_{ext}) is defined as the difference between the maximum diameter (D_{max}) of the damaged zone and the nominal exit hole diameter (D_{nom}).

$$D_{ext} = D_{max} - D_{nom} \quad (1)$$

Figure 4 shows a representative image for the visualization of the damage evaluated by DeFu et al. (2012).

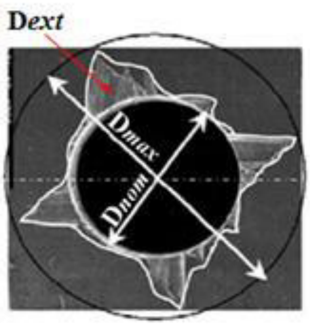


Figure 4: Typical image for the visualization of the damage.

From Figure 5, it is clear that lower water pressure (1000bar), low abrasive flow rate (5.4gm/sec) and low standoff distance (1mm and 2mm) resulted in no delamination (D_{ext} = 0). High water pressure (2500bar), high abrasive flow rate (9.7gm/sec) and high standoff distance (3mm) produced higher delamination (D_{ext} = 13.81mm), this may be due to the increase in crack length due to the increase in the water pressure as reported by Shanmugam et al (2008). An increase in kinetic energy of the water jet would be a contributing factor for the increased rate of propagation of cracks.

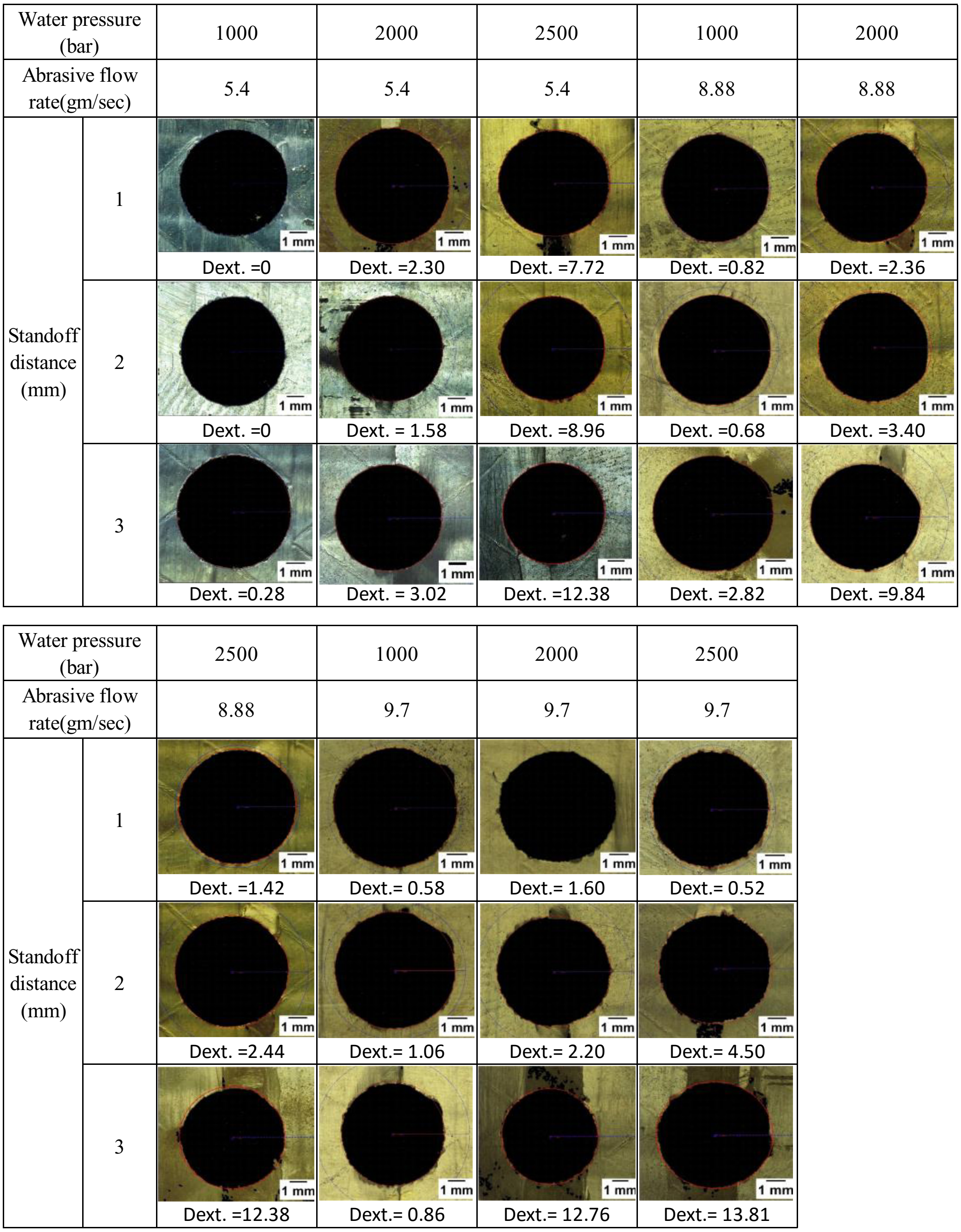


Figure 5: Morphology for exit drilled hole at different water pressure, abrasive flow rate and standoff distance, while drilling of CFRP.

3.2 Influence of the cutting parameters on the delamination extent

Analysis of variance (ANOVA) was carried out on the experimental water pressure, abrasive flow rate and standoff distance data to identify the main effects and interactions. The ANOVA performed on the delamination extent data showed that the main effects of water pressure and standoff distance were statistically significant at a risk level (α) of 5%. Further, no higher order interaction effects were found to be statistically significant at a risk level (α) of 5%. The main effect plots of the delamination extent are shown in Figures 6 (a) to 6 (c).

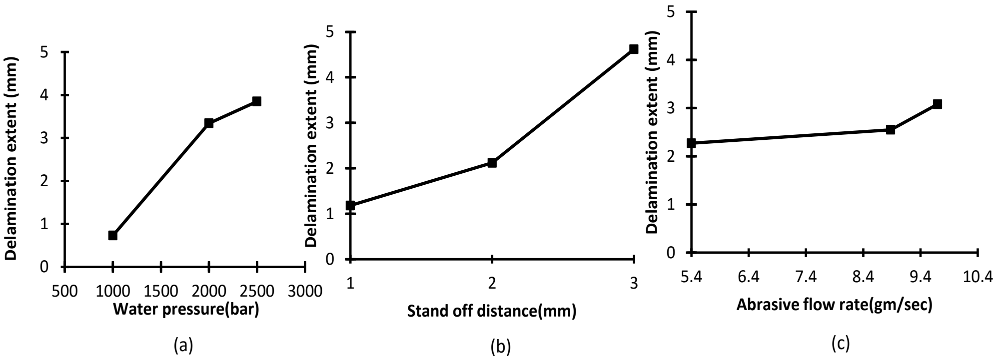


Figure 6: Main effect plot for delamination extent; (a) water pressure; (b) standoff distance; (c) abrasive flow rate.

Analysis of the results in Figure 6 (a) shows a multi-fold increase (357%) in the delamination extent as the water pressure is increased from 1000 to 2000 bar and a modest 15 % increase in the delamination extent as the water pressure is increased from 2000 to 2500 bar. It may be noted that the pressure governs the exit velocity of the jet and hence the kinetic energy which directly affects the material erosion. Higher material erosion can affect the delamination; however, the rate of increase of the delamination extent is very high from 1000 bar to 2000 bar. Increasing the water pressure further does increase the delamination extent, albeit, at a lower rate. Figure 6 (b) shows a 80% increase in the delamination extent as the standoff distance is increased from 1 to 2 mm and 118 % increase in the delamination extent as the as the standoff distance is increased from 2 to 3 mm. The closer the standoff distance, the lower the divergence of the jet and hence an increase in the extent of delamination are observed if the standoff distance is increased. Figure 6 (c) shows a 11% increase in the delamination extent as the abrasive flow rate is increased from 5.4 to 8.88 gm/sec and 21 % increase in the delamination extent as the as the abrasive flow rate is increased from 8.88 to 9.7 gm/sec. The effect of abrasive flow rate on the delamination extent is not very pronounced and, as mentioned previously, it is not a statistically significant factor either.

3.3 Influence of the cutting parameters on the exit hole size

Scott et al (2001) observed that the dimensional precision strongly affects the functional performance of the composite parts in their service life. Hence, the exit hole size was also analyzed. Analysis of variance (ANOVA) was carried out on the experimental water pressure, abrasive flow rate and standoff distance data to identify the main effects and interactions. The ANOVA performed on the exit hole diameter data showed that the main effects of water pressure and standoff distance were statistically significant at a risk level (α) of 5%. As in the case of delamination extent, no higher order interactions were found to be statistically significant at a risk level (α) of 5%. The main effect plots of the exit hole diameter are shown in Figure 7.

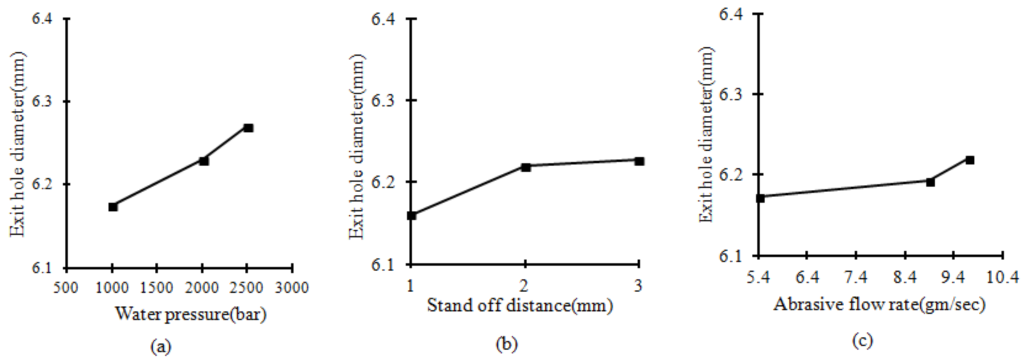


Figure 7: Main effect plots of the normalized d exit hole diameter.

Analysis of the results in Figure 7 (a) shows a linear increase in the exit hole with an increase in the water pressure. There is an increase of 0.80% in the exit hole diameter if the water pressure is increased from 1000 to 2000 bar and another 0.6 % increase if the water pressure is increased further to 2500 bar. The higher water pressures lead to higher jet velocities and higher material erosion, which increases the exit hole size. Figure 7 (b) shows a 0.97% increase in the exit hole diameter if the standoff distance is increased from 1 mm to 2 mm and an additional 0.12 % increase in the exit hole diameter if the standoff distance is increased further to 3 mm. As mentioned previously, this could be attributed to the increased divergence of the jet with an increase in the standoff distance. The effect of Figure 7 (c) shows a 0.3% increase in the exit hole diameter as the abrasive flow rate is increased from 5.4 to 8.88 gm/sec and 0.4 % increase in the exit hole diameter as the as the abrasive flow rate is increased from 8.88 to 9.7 gm/sec. The effect of abrasive flow rate on the exit hole diameter is not very pronounced as it was not found to be statistically significant in the ANOVA.

4 Delamination control techniques

Delamination is a big problem in AWJ drilling of composites. There has been a lot of work done on the delamination control in conventional drilling, primarily, by reducing the thrust force by the use of back-up plate (Capello, 2004) , pre-drilled pilot hole (Tsao and Hocheng, 2003), Peck drilling studied by (Aykut Kentli, 2011) and use of special drill bits (Durao et al., 2010). However, very little work has been reported on delamination control techniques in AWJ drilling of CFRP composites. Similar to the conventional drilling, delamination control techniques are expected to reduce the extent of delamination in AWJ drilling. Following techniques have been employed to reduce the AWJ drilling induced delamination in the present work:

- Use of backup plates
- Use of pre-drilled holes
- Water immersion (under water) drilling

4.1 Use of backup plate (Acrylic plate)

It may be noted that the delamination is observed primarily near the exit region which can be attributed to the forces applied due to the impinging jet. It has been observed that the delamination in conventional drilling occurs due to the thrust forces which result in local deformation close to the drill exit. This can be reduced by using backup plates placed under the composite laminate to prevent deformations leading to push-out delamination as demonstrated by Ramulu et al (2012). This concept has been extended for AWJ drilling and rigid support was provided to the composite laminate to prevent the deflection of the exit zone due to the impinging jet at exit region. The reduced deflection is expected to reduce the extent of delamination. The image of the CFRP plate with an acrylic backup plate is shown in Figure 8.

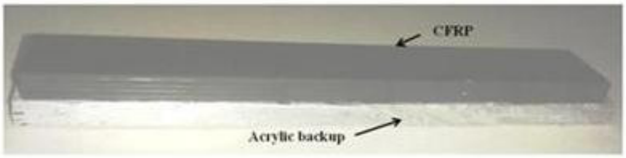


Figure 8: CFRP plate with backup acrylic plate.

4.2 Use of pre-drilled holes

Lemma et al. (2002) and Wang (2002) studied delamination often occurs due to the high velocity impact of the jet, in particular, during cutting features, such as holes or slots. Ramulu and Kraja (2002) presented a study to minimize the delamination by using a predrilled starter hole. They observed lower damage at the exit when a pre-drilled hole of 5 mm was used. The deflection in the exit zone is lower due to the impinging jet is lower in case of pre-drilled hole which can lead to reduced delamination. Pre-drilled hole of 5mm diameter was used in the AWJ drilling experiments as shown in Figure 9.

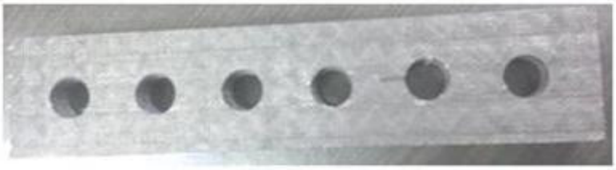


Figure 9: CFRP plate with pre-drilled hole using AWJM.

4.3 Water immersion (Under water) drilling

In this techniques material was placed under the water while drilling. It has been observed that the brittle materials can be cut without shattering under water due to the damping of energy. A similar concept has been utilized to see the effect of damping on damage propagation during AWJ drilling.

Figure 10: CFRP plate Water immersion (under water) drilling.

5 Comparative assessment delamination control techniques

In order to compare the effect of different delamination control techniques, a small full factorial design of experiment with three factors and two levels (2^3) was used to control delamination extent. The three factors and two levels are given in Table 3. This design of experiment is carried out for normal AWJ drilling and the three delamination control techniques to quantitatively compare the delamination extent as a function of the process parameters. The exit hole dimensions were also analyzed along with the delamination extent. Finally the surface roughness values have been compared at the extreme combinations of the parameters.

Table 3: Factor and their levels

Levels	Water Pressure (bar)	Abrasive flow rate (gm/sec)	Standoff distance (mm)
1	2000	8.88	2
2	2500	9.7	3

5.1 Comparison of drilled hole morphology for various delamination control techniques

The morphology of the exit side of the drilled holes at water pressure 2000 bar is shown in Fig.11.

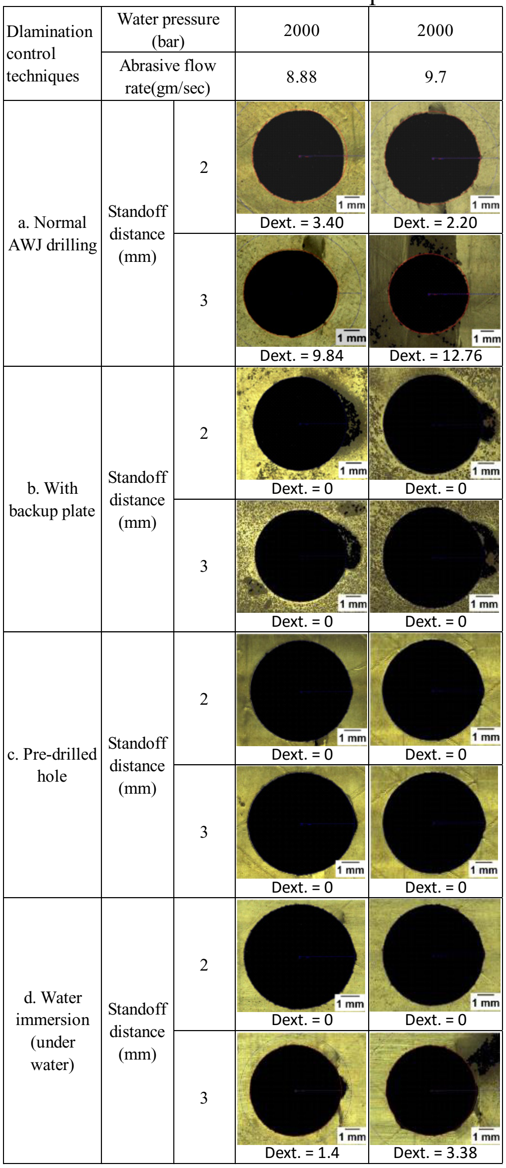


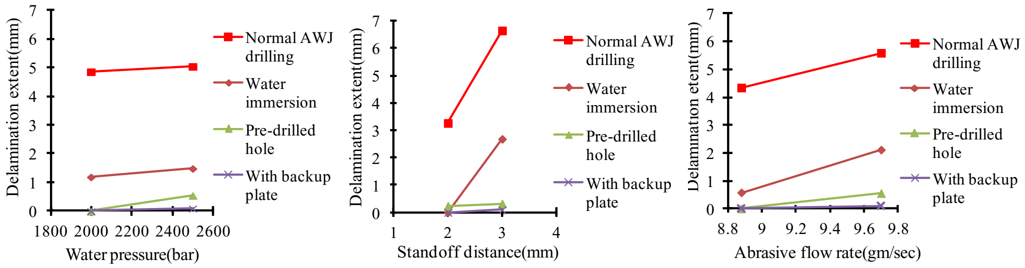
Figure 11: Morphology of the exit drilled hole at water pressure 2000 bar for different drilling conditions.

It can be clearly seen that the backup plate and the pre-drilled holes no trace of delamination extent as opposed to significant delamination extent observed if AWJ drilling of CFRP is carried out normal AWJ drilling.

The maximum extent of delamination without any delamination control method is 12.76 mm as opposed to no delamination extent observed for backup plate and pre-drilled holes. However, the water immersion (under water) does not appear to be as effective as the other two, but the maximum delamination extent is limited to 3.88 mm which is still much better than drilling without any delamination control technique. Based on these observations it can be concluded that the delamination control techniques are very effective and should be used in the AWJ drilling of composites.

5.2 Quantitative comparison of drilled hole for delamination extent for different delamination control techniques

Analysis of means is used to present the effect of various parameters on delamination extent. The delamination extents in normal AWJ drilling and drilling with different delamination control techniques are plotted as a function of various process parameters.



(a) (b) (c)

Figure 12: Main effect plots of the comparison of drilled hole for delamination extent: (a) Water pressure; (b) Standoff distance; (c) Abrasive flow rate.

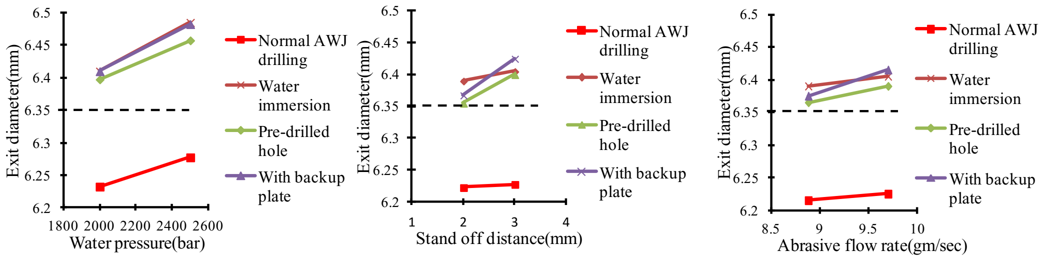
Analysis of the results in Figure 12 (a) shows that there is a significant delamination (~5 mm) if normal AWJ drilling is carried out, whereas there is no trace of delamination with pre-drilled hole and a backup plate at 2000 bar. The water immersion technique is also beneficial and there is a 76% decrease in the delamination as compared to normal AWJ drilling at 2000 bar. An increase in the water pressure to 2500 bar does not affect the delamination significantly, and except for the pre-drilled hole, the delamination extent remains almost constant even with an increase in the pressure. Based on the observations, it can be seen that the backup plate is the most effective technique to reduce drilling-induced delamination as it can effectively reduce the deflection in the exit zone by providing addition strength. The pre-drilled hole is the second best technique, but at higher pressures, a slight delamination of 0.55 mm is observed. Even though water immersion can reduce the delamination by damping the energy, this technique is not as effective as the backup plate.

Figure 12 (b) shows the effect of standoff distance. Note that the standoff distance is the most prominent factor as observed in the analysis of normal AWJ drilling. All the delamination control techniques work effectively at a lower standoff distance of 2 mm, but if the standoff distance is increased to 3 mm, the water immersion technique is rendered ineffective. However, the other two techniques are still very effective. Based on these results, it can be concluded that the backup plate is the most suitable technique for the delamination control, followed by the pre-drilled hole and the water immersion techniques. Consequently, it can be inferred that physical strengthening mechanism which restricts the deformation can control the delamination more effectively than the energy damping offered by the water immersion technique.

Figure 12 (c) shows the effect of abrasive flow rate on delamination extent. Similar to the water pressure and standoff distance, the delamination control techniques are fairly effective. However, there is a slight increase in delamination extent even with the delamination control techniques (except back up plate) if the abrasive flow rate is increased due to an increase in the kinetic energy imparted.

5.3 Comparison of drilled hole for exit hole diameter

Figures 13 (a) to (c) show the exit diameter as a function of process parameters for different delamination control techniques. It may be noted that the delamination extent and exit hole diameter may not be correlated and the geometrical accuracy of exit hole needs to be ascertained for different techniques. The desired hole size was 6.35 mm which is shown as the dashed line in all the plots in Figure 13.



(a) (b) (c)

Figure 13: Main effect plots of the comparison of drilled hole for exit hole diameter.

Analysis of the results in Figure 13 (a) shows that the effect of the water pressure is not very significant and less than 1% increase in the exit hole diameter as the water pressure is increased from 2000 to 2500 bar for all the experimental conditions. It is very interesting to note that the normal AWJ drilling results in undersized holes whereas if the delamination control techniques are used the holes are slightly oversized. The hole dimensions are closer to the nominal dimension (~0.7% error) if the delamination control techniques are used at 2000 bar. In case of the conventional drilling the geometric errors are about 2%. Unlike the delamination control techniques where the backup plate yielded the lowest delamination extent, the lowest geometric error is obtained in the pre-drilled hole. The geometric errors increase with an increase in the water pressure for all the conditions. Figure 13 (b) shows a similar trend and the pre-drilled hole out perform all other techniques and an increase in the standoff distance increases the geometric errors. Figure 13 (c) also shows that the pre-drilled hole is the best technique, whereas water immersion (under water) and backup plate yield better dimensional accuracy at high and low abrasive flow rates, respectively. Even though all the three techniques produce slightly oversized holes the errors are lower using the delamination control techniques.

5.4 Comparison of drilled hole for surface roughness

Surface roughness is one of the most important parameter in machining process. Hole surface quality will strongly affect the parts during their service life, especially, in the cases of the components in contact with other elements or materials. Poor hole surface roughness also affects the fatigue life of hole. Average surface roughness value, R_a, was used to characterize the hole surface quality via focus variation microscopy (Alicona, Infinite Focus G4). Since the measurement required cutting the drilled hole to expose it for optical metrology, a limited number of readings have been acquired. The surface roughness has been characterized for extreme conditions (lowest values of all three parameters and highest values of all three parameters given in Table 3) for all the four conditions (one normal and three delamination control techniques). Comparison of drilled hole surface roughness for different delamination control techniques as shown in Figure 14.

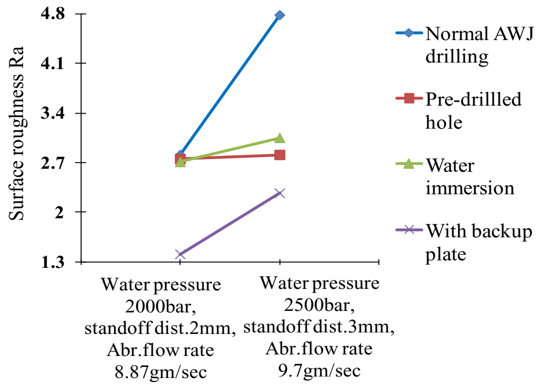
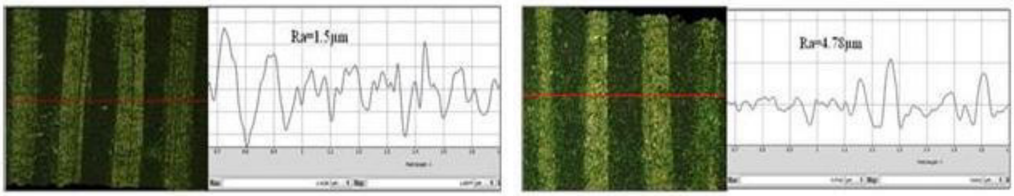


Figure 14: Comparison plot of drilled hole surface roughness for different delamination extent control methods.



(a) (b)

Figure 15: (a) With backup plate, (b) Without backup plate hole surface roughness images.

Figure 14 shows that the best surface finish is obtained for the backup plate, whereas the worst surface finish is obtained normal AWJ drilling. This is clearly depicted in the surface profiles shown in Figures 15 (a) and (b). An increase in the water pressure the kinetic energy of the abrasive particles increase, high standoff distance results in the divergence of the jet prior to impingement and the higher abrasive flow rate may result in increased scratches on the hole surface, hence, the surface roughness worsens if any or all of these parameters in increase. Similar observations have been made by Azmira and Ahsan (2009).

6 Conclusions

This study is focused on the comprehensive characterization of delamination extent and hole geometry as a function of process parameters in the abrasive water jet drilling of CFRP. In addition, a comparative study of different delamination control techniques on the delamination extent and geometric error has been carried out. Finally, the surface roughnesses have been compared at extreme conditions for all four cases. Following specific conclusions can be drawn from the present work:

- The ANOVA performed on the delamination extent data showed that the main effects of water pressure and standoff distance were statistically significant at a risk level (α) of 5%. There is a multifold increase (> 4 times) in the delamination extent, if either the water pressure is increased from 1000 bar to 3000 bar or the standoff distance is increased from 1 mm to 3 mm. The increase in delamination could be attributed to the increased kinetic energy in case of water pressure and higher jet divergence at higher standoff distances.

- The exit hole measurement also showed that the main effects water pressure and standoff distance were statistically significant at a risk level (α) of 5%. There is an increase of 43% in the exit hole diameter if the water pressure is increased from 1000 bar to 3000 bar. There is an increase of 46% in the exit hole size if the standoff distance is increased from 1 mm to 3 mm. Increased material erosion due to higher kinetic energy and larger area cut due to jet divergence can explain the increase in exit hole size.
- The delamination extent is reduced significantly if the delamination control techniques are used. The best delamination control technique is backup plate followed by pre-drilled hole and water immersion (under water). Backup plate is extremely effective as the deflection of the exit zone is reduced significantly via the strengthening mechanism which reduces the push out delamination.
- The hole size analysis revealed that normal AWJ drilling always yields undersized holes whereas if the delamination control techniques are used the holes are slightly oversized. However, the geometric accuracy of the holes is better if a delamination control techniques is used. The best geometrical accuracy is obtained with the pre-drilled holes which could be attributed to smaller volume of material erosion required during drilling.
- The surface finish of the AWJ drilled holes improve if lower values of water pressure, standoff distance and abrasive flow rate are used. Drilling with a backup plate yields the lowest roughness values.

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